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Performances of a Linear Type Magnetic Flux Pump for Compensating a Little Decremented Persistent Current of HTS Magnets

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***Abstract*—This paper describes the characteristics of a linear type magnetic flux pump recently developed. The linear type flux pump has been fabricated to apply to compensate decremented persistent current of HTS applications such as NMR and MRI system. The linear type magnetic flux pump mainly consists of 3-phase AC armature coil, DC bias coil and superconducting Nb foil. In the preliminary experiment, the flux pump can charge the pumping-up current in the load coil of 1.3 mH during 1000 seconds under the DC bias current of 10 A and 3-phase AC of 8 A, 60 Hz. The magnitude of pumping current is 0.1 mA/s.**

***Index Terms*—Linear type magnetic flux pump, Nb foil, persistent current compensation.**

I. Introduction

SUPERCONDUCTING flux pump [1], [2] and superconducting rectifier have been proposed and developed for the past about fifty years. Most recently, the application for the superconducting power supply is very promising in high-T_c superconducting (HTS) coils applications such as magnetic resonance image-CT (MRI-CT) and nuclear magnetic resonance spectrometer (NMR) used for life science fields. Compared with low-T_c superconductors (LTS), since HTS coils have a low n-index, HTS coils could not keep the persistent current constant substantially [3], [4]. The linear type magnetic flux pump makes less vibrations and electric noises than the early-developed flux pump [5]–[7]. Consequently, a static linear type magnetic flux pump would be thought to be most suitable to compensate the decremented persistent current. Presently, the system of the flux pump has been performed for R&D on current compensation source. In this experiment we observed the pumping-up current in the load coil to measure small quantities of pumping current.

We determined the ramping up rates of pumping current in the load coil under the DC bias current of 10 A and the 3-phase AC current of 8 A during 1000 seconds. The magnitude of pumping current is about 0.1 mA/s. The main purpose of this study is to obtain the design and manufacturing techniques for the compensator of decremented persistent current in the HTS magnet system.

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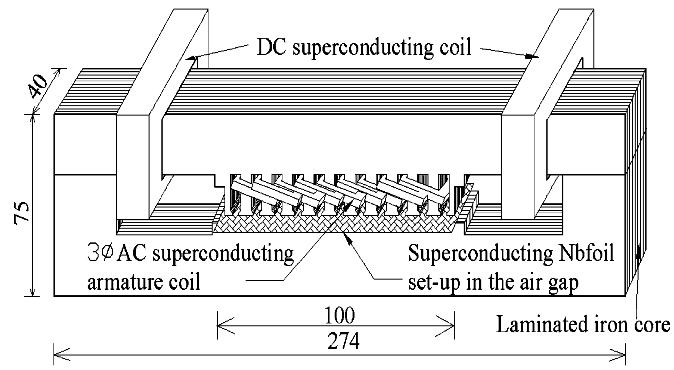

Fig. 1. Schematic diagram of the linear type magnetic flux pump.

II. Basic Structure and Concept

A. The Structure of the Linear Type Flux Pump

The linear type flux pump is mainly composed of four components as follows:

1) Laminated linear core,
2) DC coil,
3) 3-phase AC coil,
4) Superconducting Nb-foil.

The linear core of the flux pump was laminated to reduce eddy-current loss. NbTi conductors for DC are used as magnet coils; including a load coil of the flux pump. NbTi conductors for AC coils are used for 3-phase AC armature coils. A sheet of superconducting Nb foil, 20 μm thick, 60 mm wide, 120 mm long, is set-up in the air gap of 3 mm. The cover for superconducting Nb foil, which is made of translucent aluminum nitride ceramic, is installed to fix the Nb foil with high thermal conductivity. The connection between the load coil and the Nb foil is done by spot welding method.

Table I provides parameters for DC coil, load coil and 3-phase AC coil.

B. The Concept and Operation of the Flux Pump

Fig. 2 shows the schematic plot about magnetic flux density distributions in the air gap. The wounded AC armature coil, 3-phase and 2-pole, produces the traveling magnetic field. On the other hand, the DC coil produces some bias magnetic field, which contributes to move up the magnetic field near the zero level of magnetic flux density because the value of critical magnetic flux density is near the zero level as shown in Fig. 2. The DC bias current in the linear type flux pump produces a constant bias component. The homopole traveling wave by the DC bias

TABLE I
PARAMETERS OF COILS

DC COIL	
Wire	NbTi /Cu (1/3.3)
Wire diameter [mm]	0.9
Turns / coil	132
Length / coil [m]	23
Inside dimension [mm^2]	3 × 4.6
Outside dimension [mm^2]	4.8 × 6.2
LOAD COIL	
Wire	NbTi /Cu (1/3.3)
Wire diameter [mm]	0.9
Turns / coil	142
Length / coil [m]	72
Inner diameter [mm]	ϕ 40
Outer diameter [mm]	ϕ 80
Inductance [mH]	1.3
3-PHASE AC COIL	
Wire	NbTi
I_c @ 4.2 K, 50 Hz [A_{peak}]	42
Wire diameter [mm]	0.6
Turns / phase	40
Total length / phase [m]	25

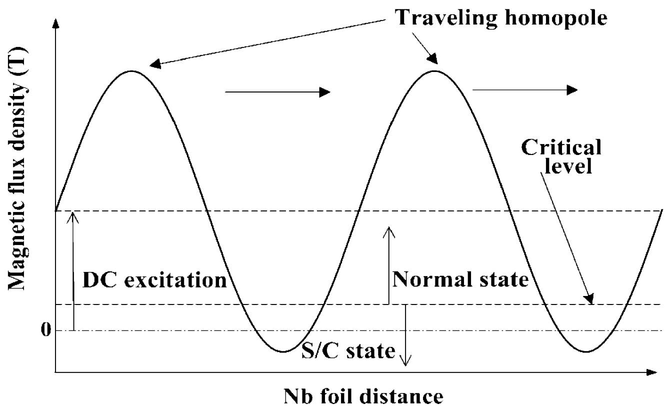

Fig. 2. Schematic plots for the superconducting Nb foil with DC and 3-phase AC excitations.

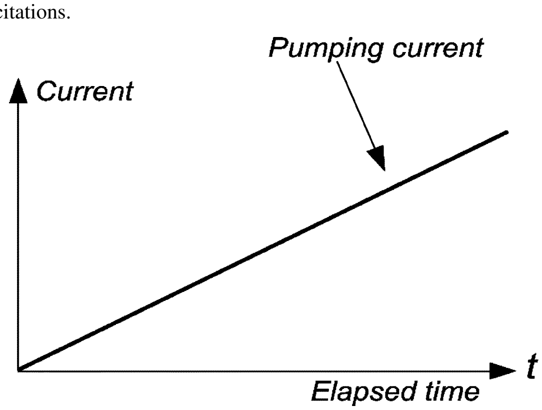

Fig. 3. Sequential diagram during the flux pump operation.

and the 3-phase AC current component produces S/N (superconducting to normal state) transitions into the Nb foil installed in the 3 mm air gap. Therefore, some magnetic fluxes can penetrate the Nb foil and the pumping-up current is accumulated in the superconductive circuit, which consists of the load coil connected to the Nb foil through superconducting wires. Although the homopolar traveling wave of Fig. 2 is an ideal sinusoidal wave, actual waveforms have many harmonics as shown in Figs. 6 and 7 later. Fig. 3 shows the ideal sequential diagram during the flux pumping operation.

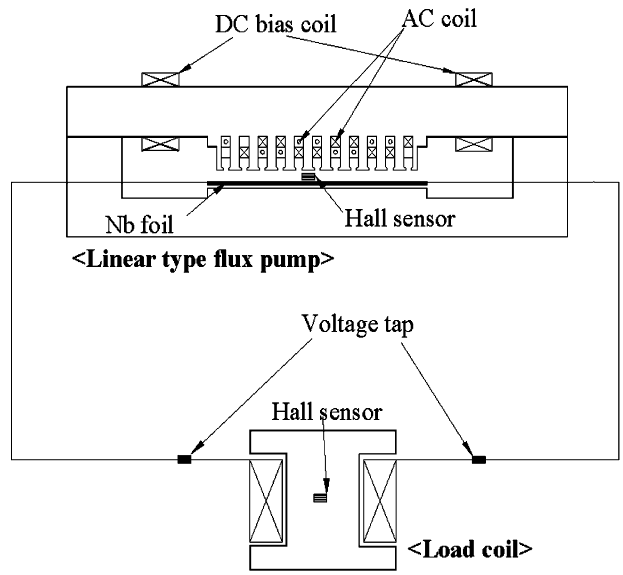

Fig. 4. Schematic diagram for the linear type flux pump system.

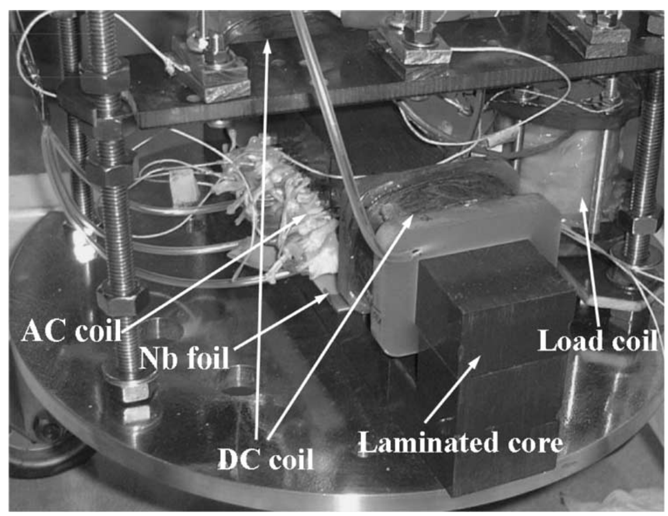

Fig. 5. Photograph of the linear type magnetic flux pump system.

III. EXPERIMENTAL SETUP

The connection diagram for experiment system circuit of the linear type magnetic flux pump system is shown in Fig. 4. In the flux pump system, 2 hall sensors are used; a transverse type cryogenic hall sensor to measure magnetic flux density at the center of the flux pump to determine the DC bias and AC excitations and an axial type hall sensor to calculate small increasing pumping current of the NbTi load coil. Also voltage tap installed both ends of the load coil. As the winding frame of the NbTi for DC coil is almost rectangular, we installed space bar at the edge part and on the surface of every layer. Inner side of the yoke of the linear type flux pump is installed with a slot liner to insulate between the laminated core and the AC coils. The DC coils and the load coil are wound on a GFRP bobbin and covered with stycast epoxy.

All signals are recorded and monitored through a data acquisition system at the same time. Shunt resistors are installed to measure the current value in the DC and 3-phase AC coils. All signals are passed through isolation amplifiers before being recorded in the recorder. Fig. 5 shows a photograph of the linear type magnetic flux pump system.

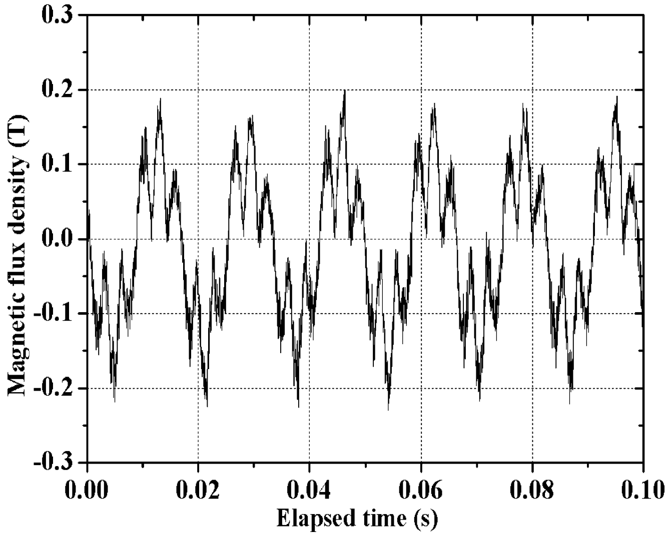

Fig. 6. Measured magnetic flux density at the linear type flux pump with 3-phase AC 8 A excitations at 60 Hz.

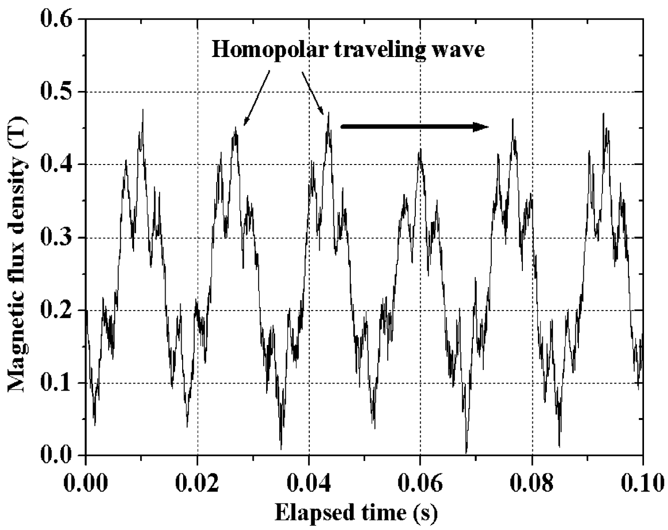

Fig. 7. Measured magnetic flux density at the linear type flux pump with DC bias of 10 A and 3-phase AC of 8 A excitations.

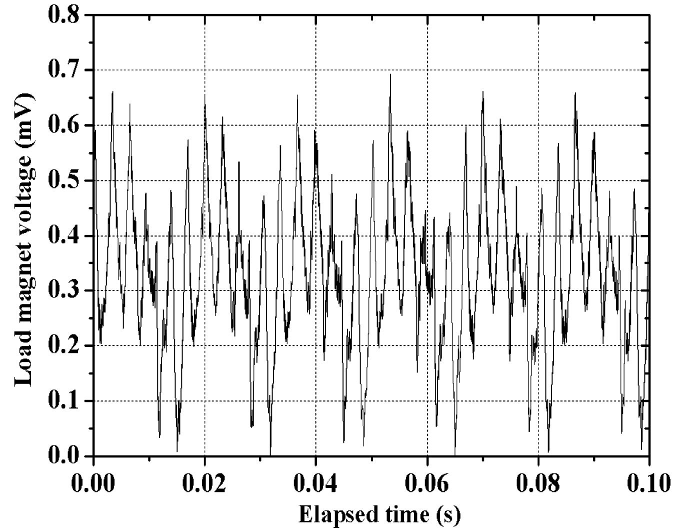

Fig. 8. Measured the load magnet voltage at 60 Hz.

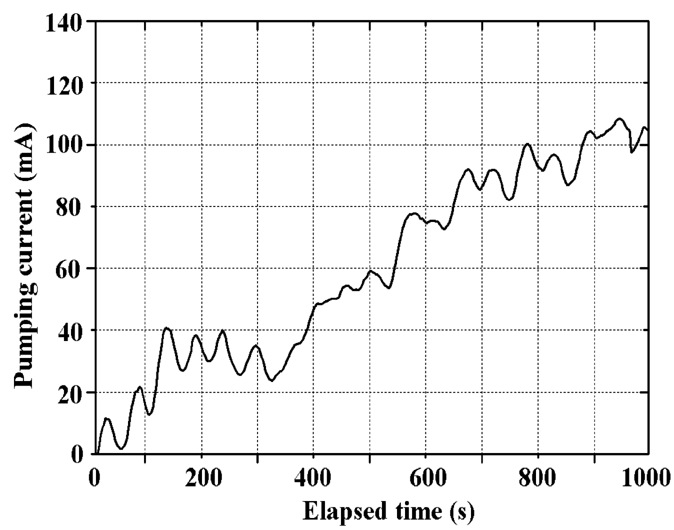

Fig. 9. Measured pumping-up current in the load magnet at 60 Hz.

IV. Results and Discussion

The pumping current and the magnet terminal voltage have been measured under the DC bias of 10 A and the 3-phase AC of 8 A at 60 Hz. The examined magnetic flux density in the central air gap for the 3-phase AC of 8 A at 60 Hz is shown in Fig. 6. The maximum and minimum magnetic flux densities are about 0.2 T and −0.2 T, respectively. Fig. 7 shows the magnetic flux density in the central air gap for the DC bias of 10 A and the 3-phase AC of 8 A at 60 Hz. The maximum and minimum magnetic flux densities are about 0.45 T and 0.05 T. Fig. 8 shows the measured result of the load magnet voltage. Fig. 9 shows the measured pumping-up current during 1000 seconds. The pumping rate is about 0.1 mA/s. Through this preliminary test, we investigated that the pumping-up current at 60 Hz contained some fluctuations because the actual homopolar traveling wave form included some harmonics as shown in Figs. 6 and 7. Therefore, based on the measured result, it was investigated that the flux pump is required to reduce the harmonics of the homopolar traveling wave to obtain stable pumping-up current.

At the next stage, the flux pump will be tested under various frequencies of 3-phase AC current and magnitudes of AC current to control pumping-up current.

V. Conclusion

In this preliminary experiment, we have fabricated the linear type magnetic flux pump for compensating decremented persistent current of HTS magnets. It has been concluded that pumping rate reached about 0.1 mA/s under the DC current of 10 A and the 3-phase AC current of 8 A at 60 Hz. Based on the test, we obtained the design and manufacturing techniques for the persistent current compensator of HTS superconducting applications.

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